Ultra-high Q whispering-gallery microcavities for narrow-linewidth lasers and optoelectronic oscillators

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Microspheres: a solid state microcavity with submillemeter dimensions and the $Q=10^{8}...10^{10}$ typical for high-finesse Fabry-Perot

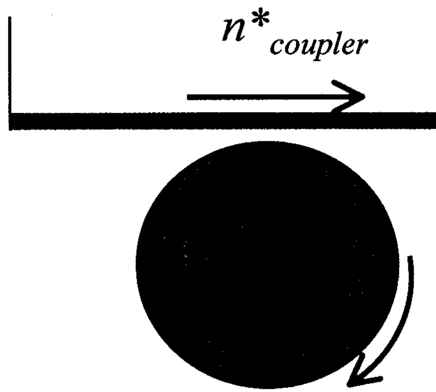
POTENTIAL FOR NARROW LINE, STABILITY LASERS AND OPTOELECTONIC MICROWAVE OSCILLATORS

• Diode laser stabilization:	optical locking by intrinsic feedback
• Microlasers:	low-pump power, narrow-linewidth source
• Optoelectronic oscillator:	low-phase-noise microwave photonic source
• Single-mode fiber and waveguide couplers:	possibility of true integration
• Novel high-finesse *spheroidal* cavity:	$F > 10^4$; true FSR ~400GHz (~3nm) in 200mkm device

State-of-the-art in coupling

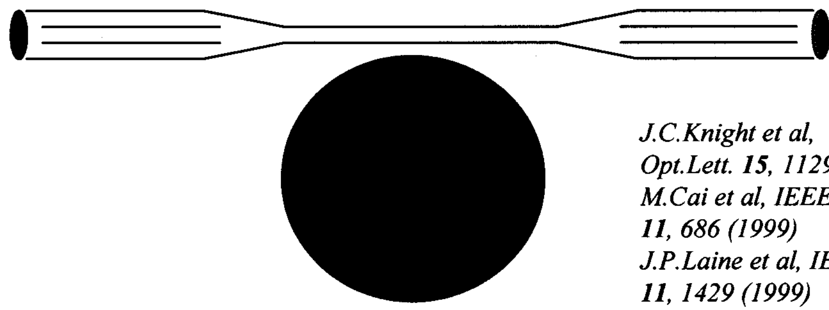
Evanescent-wave coupling: phase synchronism + near-field overlap

a. Waveguide, fiber taper: $n^*_{sphere} = n^*_{coupler}$ n^*_{sphere}, n^*_{fiber} - effective refraction indices of the WG mode azimuthal propagation and coupler mode, respectively



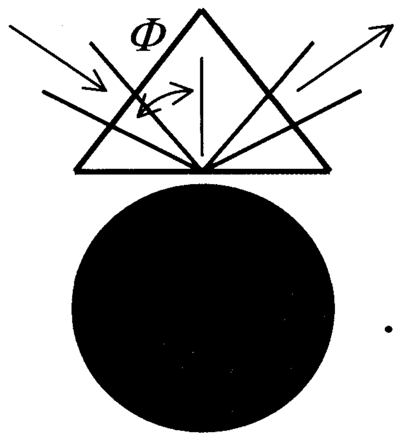
n^*_{sphere}

B.E.Little et al
Opt.Lett. ***24****, 73 (2000)*



J.C.Knight et al,
Opt.Lett. ***15****, 1129 (1997)*
M.Cai et al, IEEE PTL,
11*, 686 (1999)*
J.P.Laine et al, IEEE PTL
11*, 1429 (1999)*

b. Prism and (novel) angle-polished fiber: $\Phi = arcsin(n_{sphere}/n_{coupler})$



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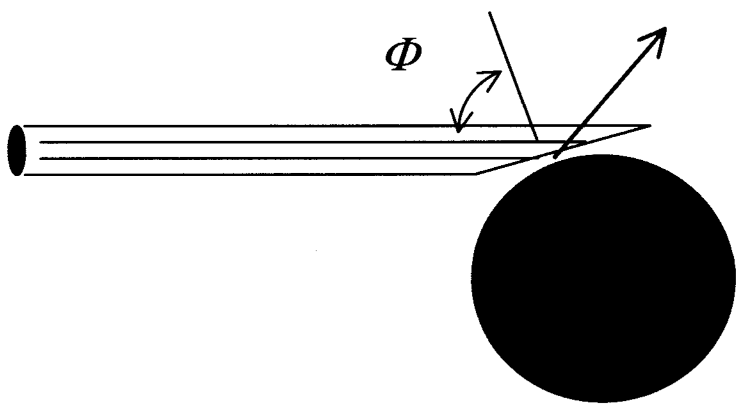
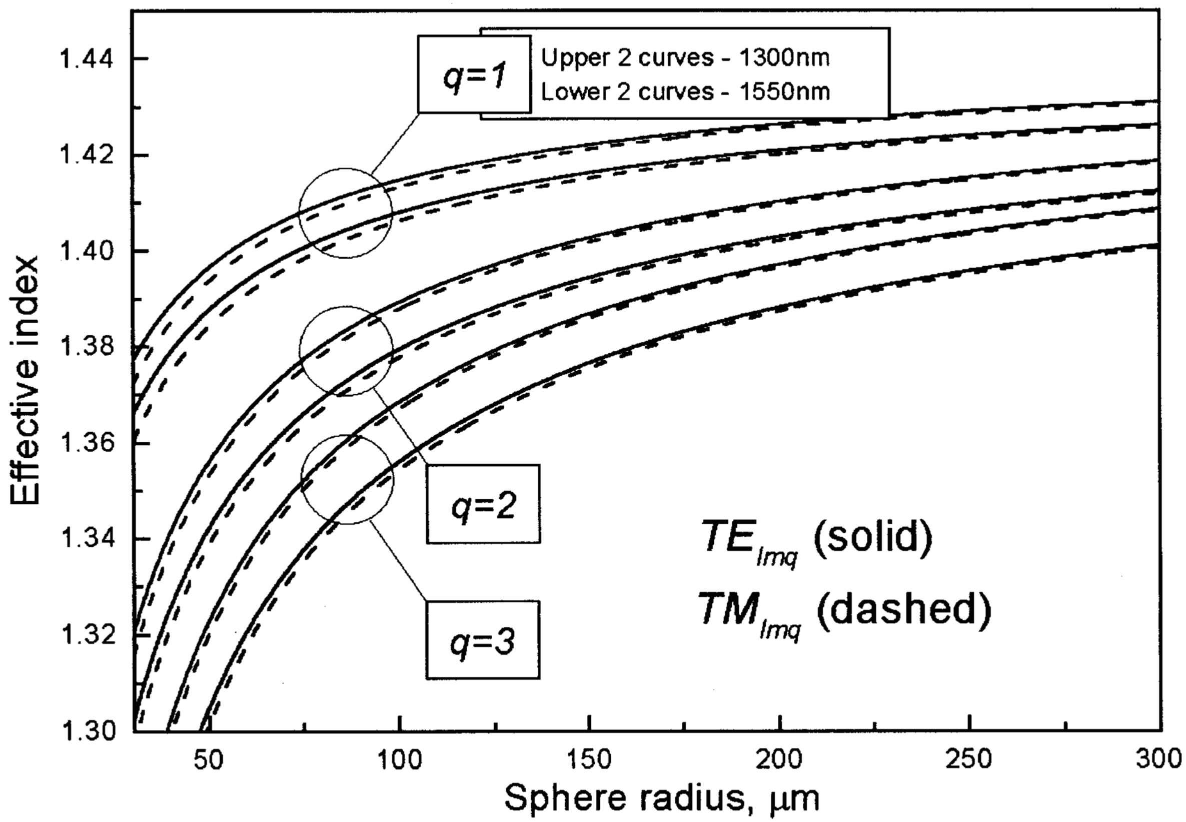


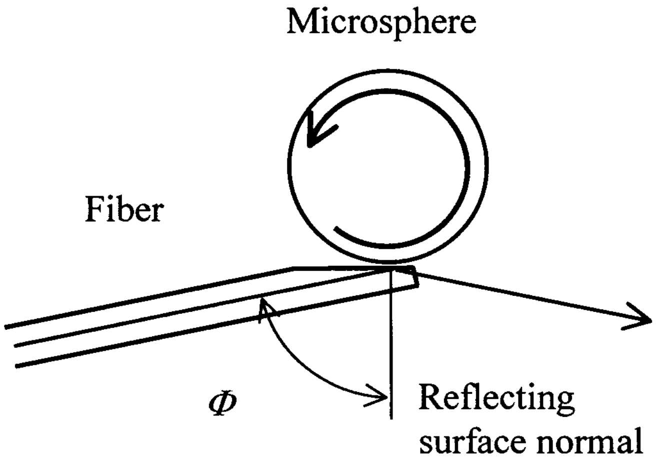
V.S.Ilchenko, X.S.Yao, L.Maleki
Opt.Lett. ***24****, 723 (1999)*

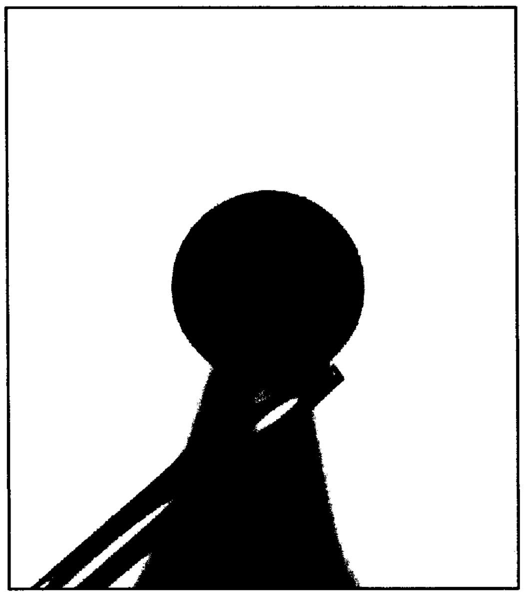
"Dispersion" of WG modes in microspheres

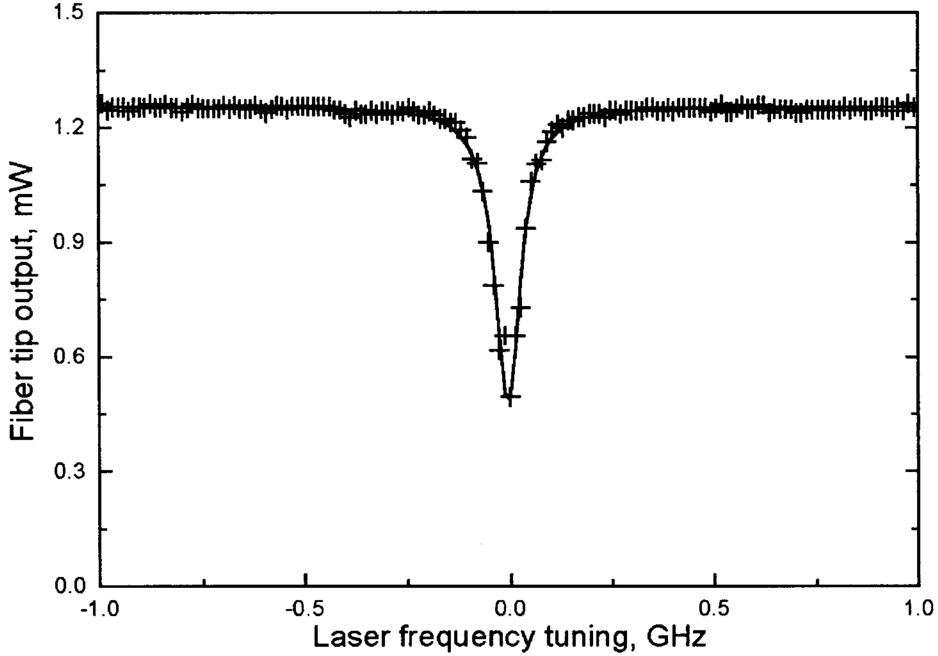


Effective refraction index for azimuthal propagation of TE_{lmq} (solid) and TM_{lmq} (dashed) modes in silica spheres at 1310nm (based on WG mode frequency approximation by *C.C.Lam et al J.Opt.Soc.Am.* ***B9****, 1585 (1992)*

Simple fiber coupler

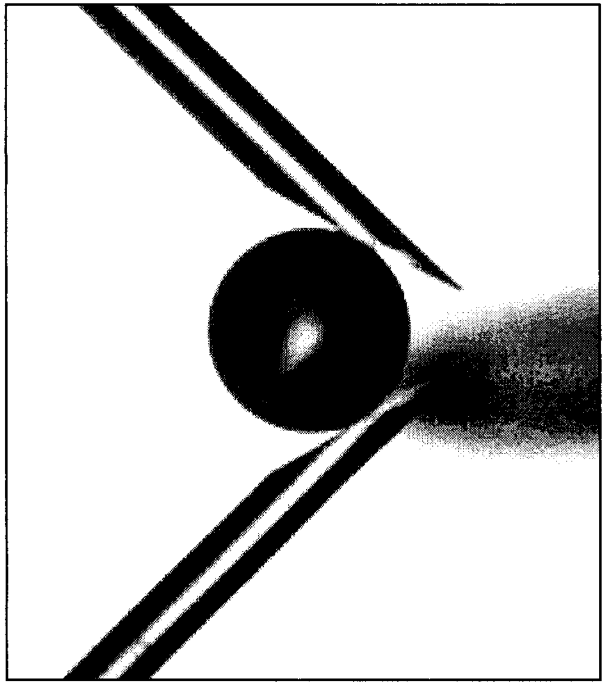


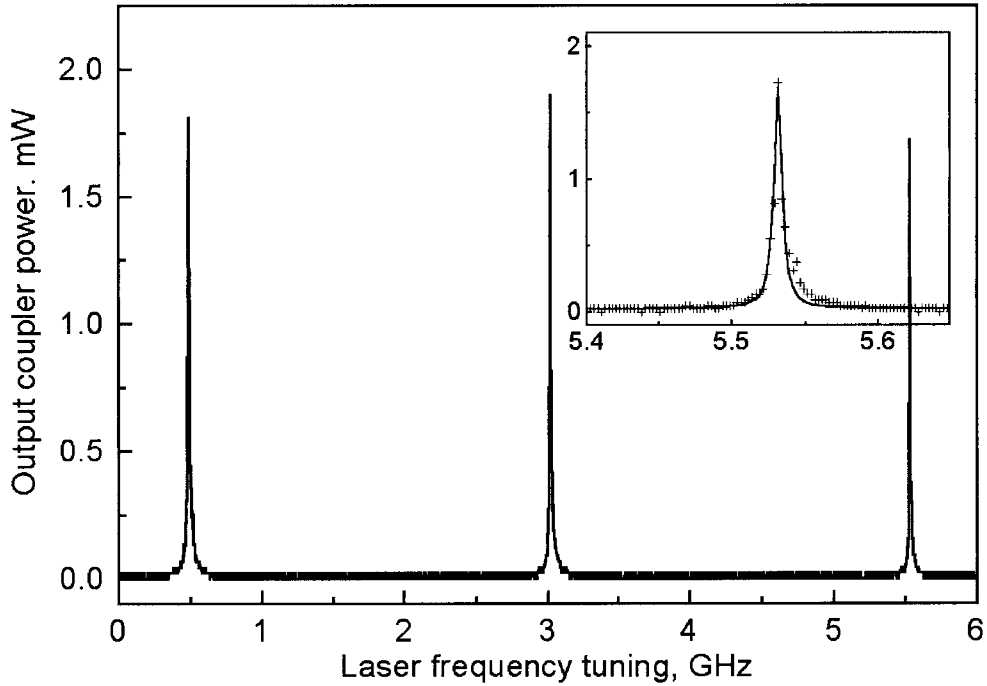




Energy coupling efficiency at resonance over 60%
(single-coupler insertion loss ~2.1dB);
$Q_{load} = 3.2 \times 10^6$ at 1310nm;
sphere diameter 470μm.

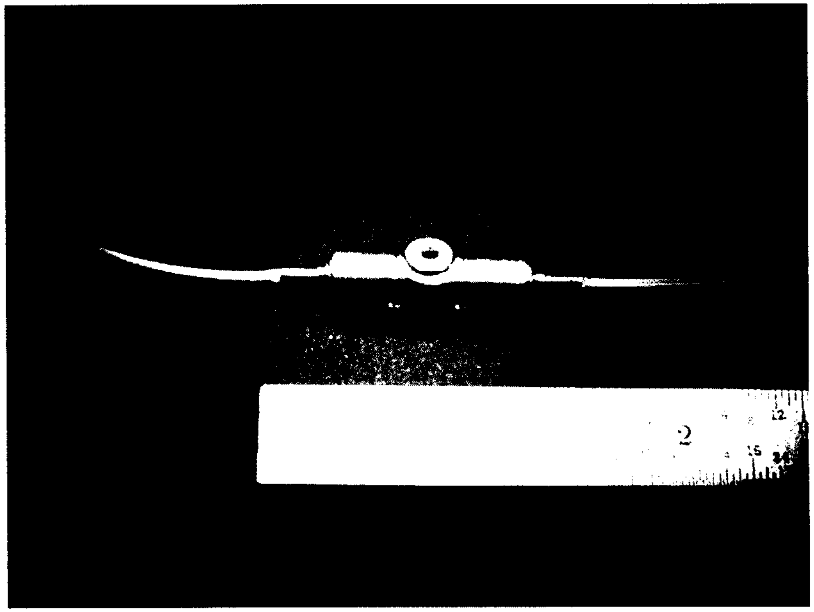
Simple fiber coupler

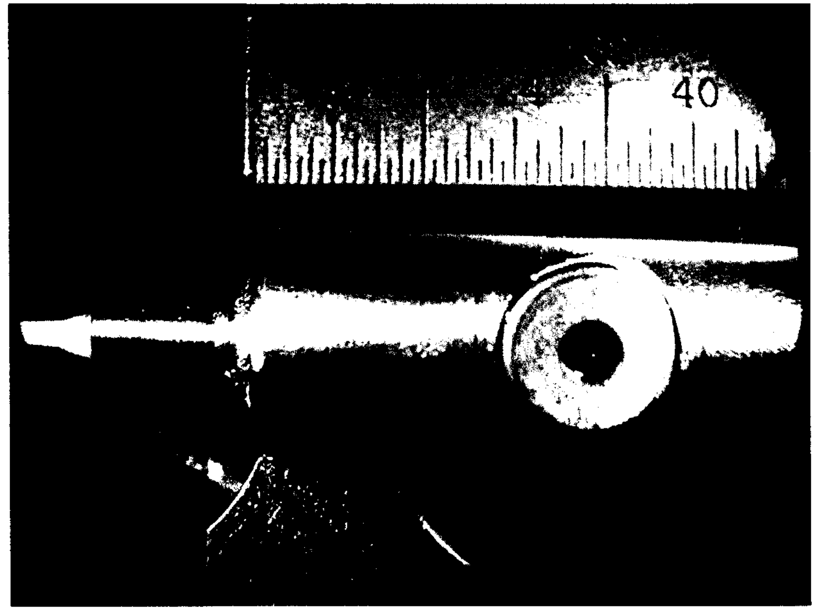




Maximum transmission at resonance ~23.5% (fiber-to-fiber loss 6.3dB);
$Q_{load} > 3 \times 10^7$ at 1550nm; sphere diameter 405μm. Unloaded $Q_o \approx 1.2 \times 10^8$.

Pigtailed microsphere package

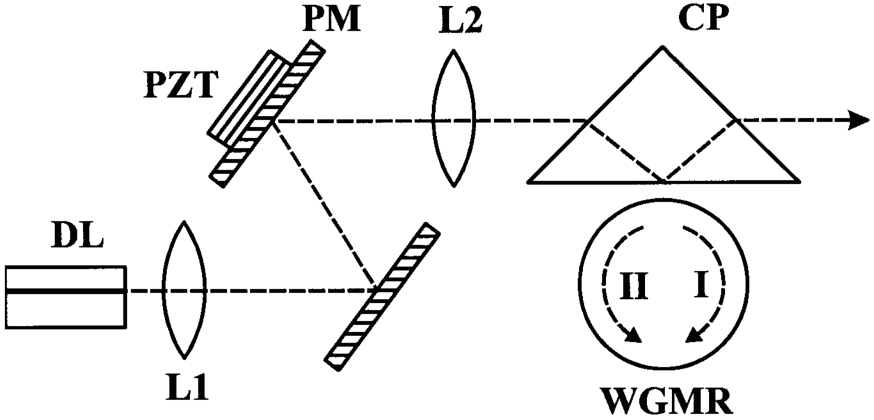




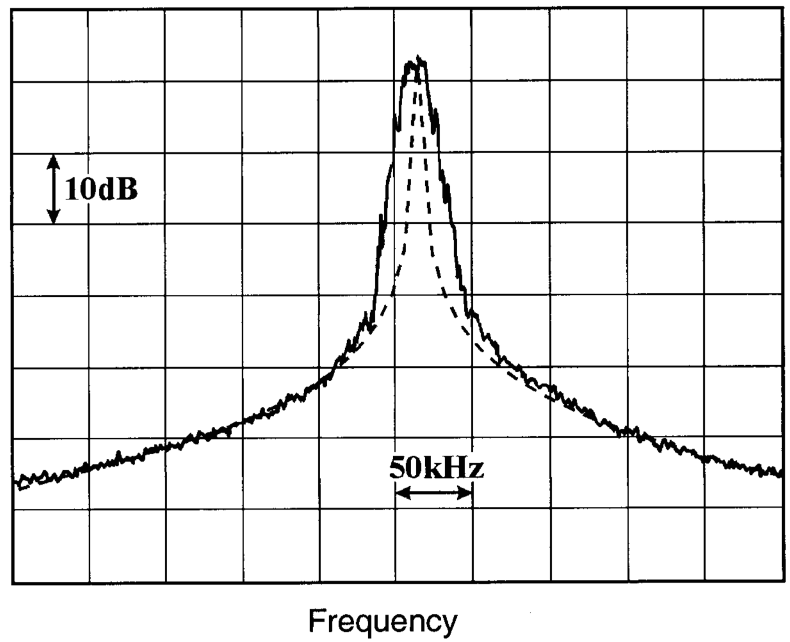
A prototype fiber pigtailed microsphere package.
Insertion loss ~12dB; loaded Q~3×10^7 at 1550nm

Microspheres for optical frequency locking in diode lasers

Intracavity Rayleigh scattering couples degenerate opposite-directed WG modes *LaserPhysics2,1004(1992), Opt.Lett.,20,1835 (1995)*-> resonance optical feedback -> optical locking of diode lasers



Frequency locking of diode laser to high-Q microsphere cavity microsphere resonator (WGMR):



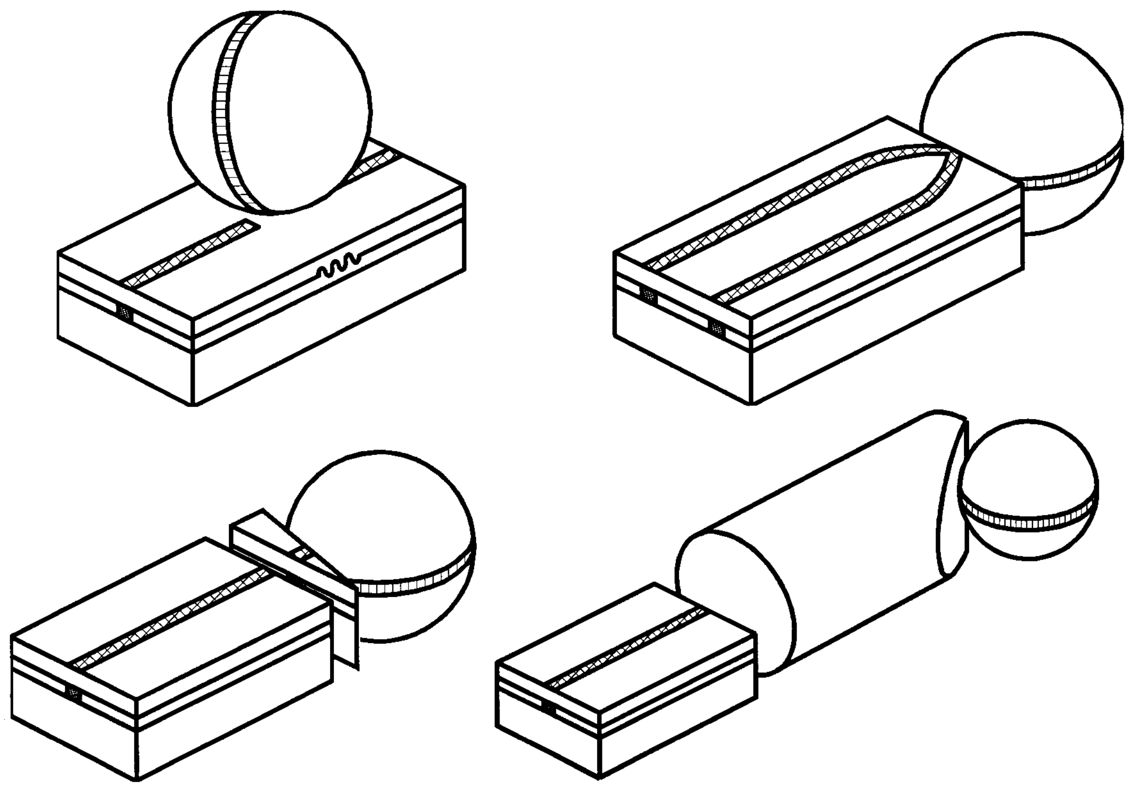
Power spectrum of 607MHz beatnote between two lasers locked to orthogonal-polarization modes in a microsphere.

Free-running laser linewidth ~15MHz, loaded Q of the sphere 5×10^7 (unloaded $Q=1.1\times10^9$); wavelength $\lambda=850nm$, sphere diameter $D=370\mu m$

Dashed line is the lorentzian fit with natural linewidth parameter 720Hz

Microspheres for optical frequency locking in diode lasers

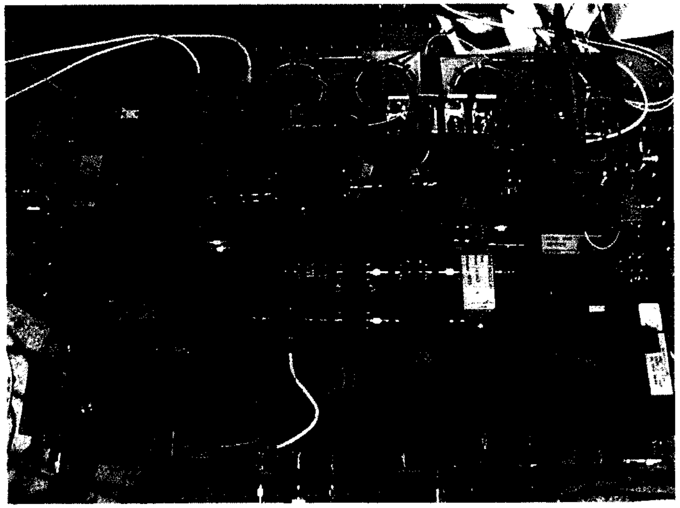
Close integration of microspheres with laser diode chips enables creation of ultra-compact sub-kHz linewidth laser sources

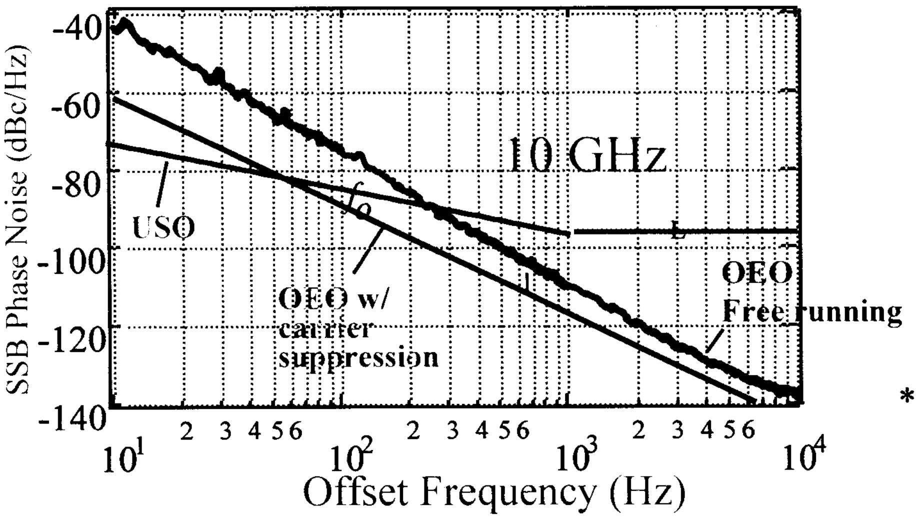


Topologies suggested V.V.Vassiliev, V.L.Velichansky, V.S.Ilchenko, M.L.Gorodetsky, L.Hollberg, A.V.Yarovitsky, "Narrow-linewidth diode laser with a high-Q microsphere resonator", *Opt.Commun.*, **158**, 305-12, 1998.

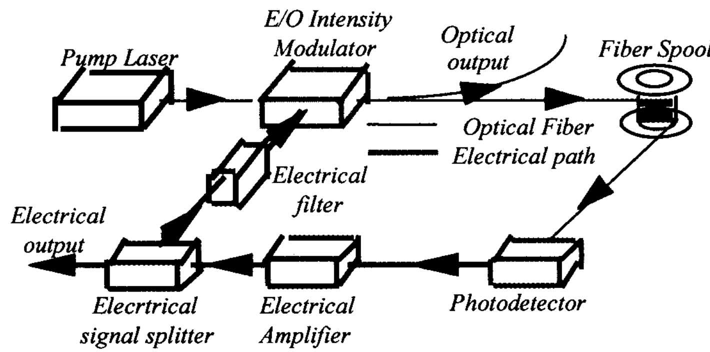
OptoElectronic Oscillator

A Bench Top 10 GHz OEO





A Typical OEO Setup



Oscillation condition:

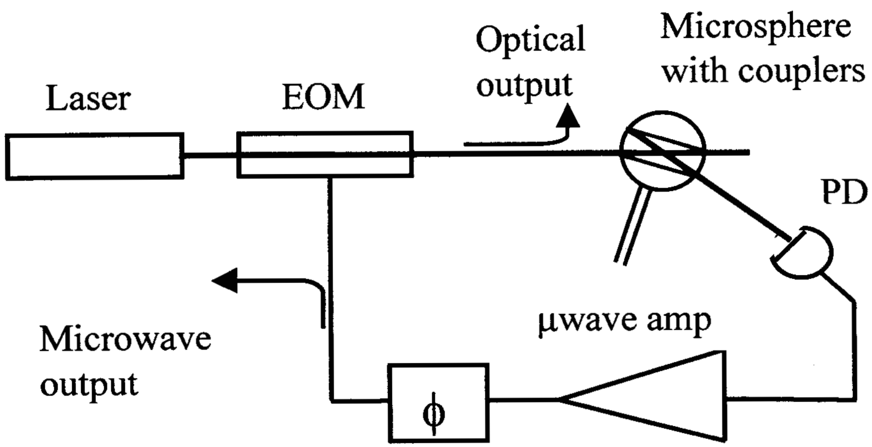
$$\Phi = 2\pi f_o L/c = m2\pi$$

$$Q = 2\pi f_o L/c \qquad L \ : \text{loop length}$$

* Very small phase noise -140dBc/Hz @ 10GHz, 10kHz from carrier

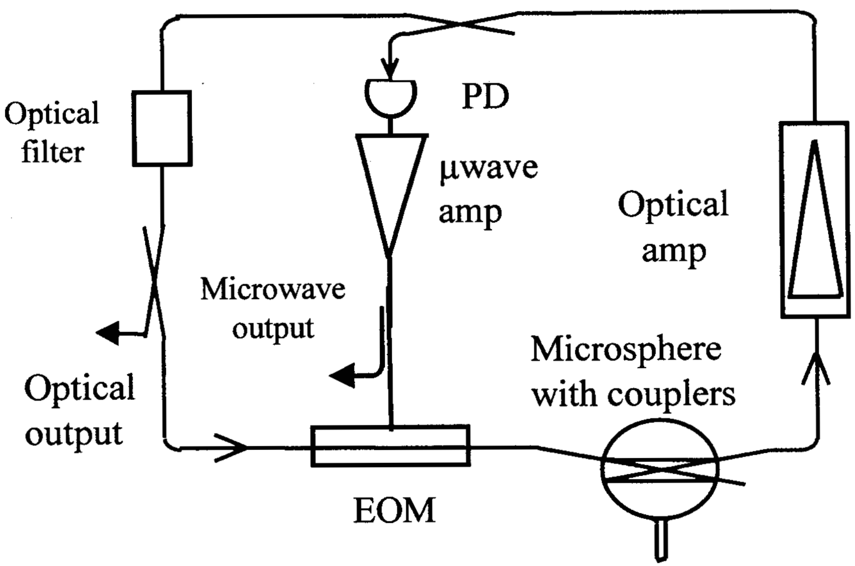
* Effective **microwave Q scales up** with frequency; components for ≥40 GHz available-> improved potential at mm-wavelengths

Two variants of microsphere-based OEO



- With external laser locked to a WG mode; microsphere acts as a high-Q MW sideband filter

WG mode selection provided by laser locking



- Based on a ring laser containing a microsphere and an optical amplifier

WG mode selection provided by optical filter inside the ring

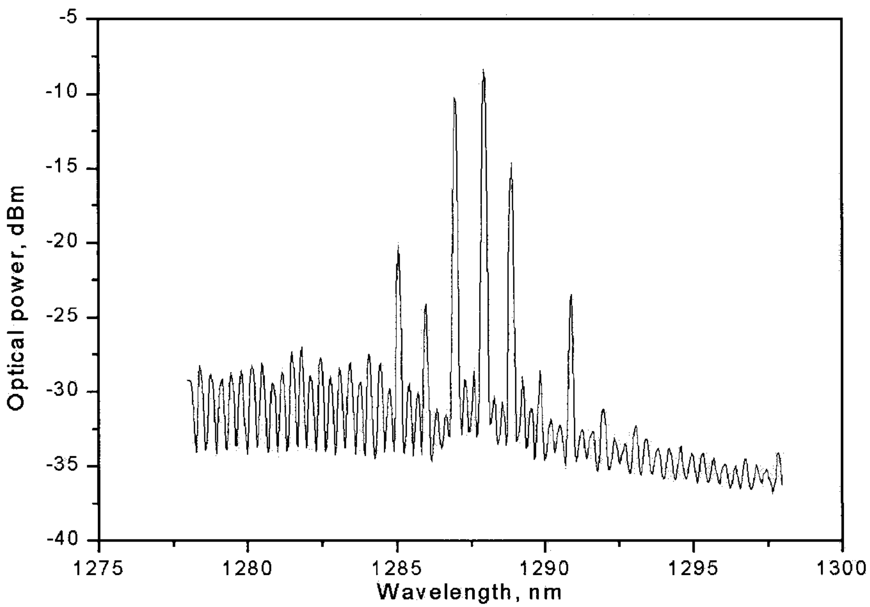
Microsphere-based OEO

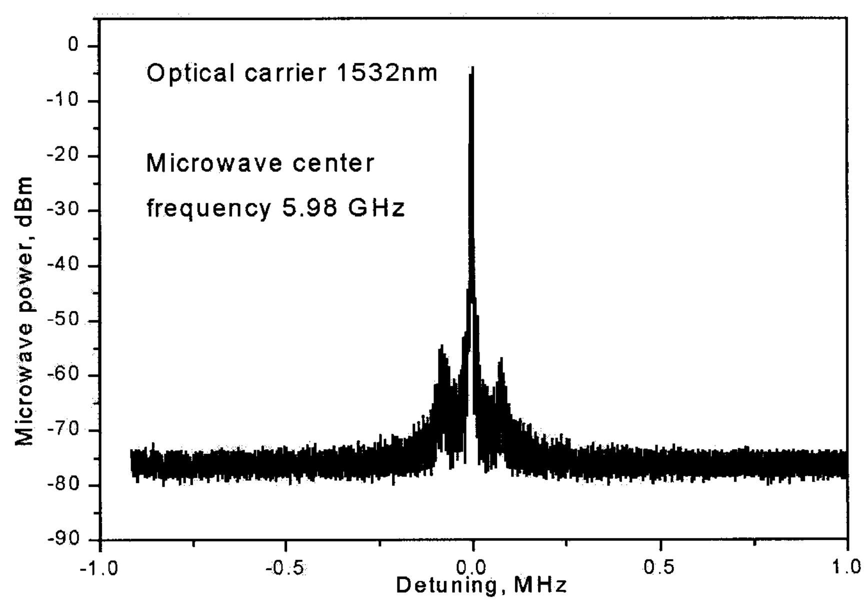
Optical spectrum of the microsphere-based ring laser. Semiconductor optical amplifier (E-Tek LDOA-1300). Microwave loop open; no optical filter

Spectrum contains several components separated by 0.98nm - "large" free spectral range of the sphere.

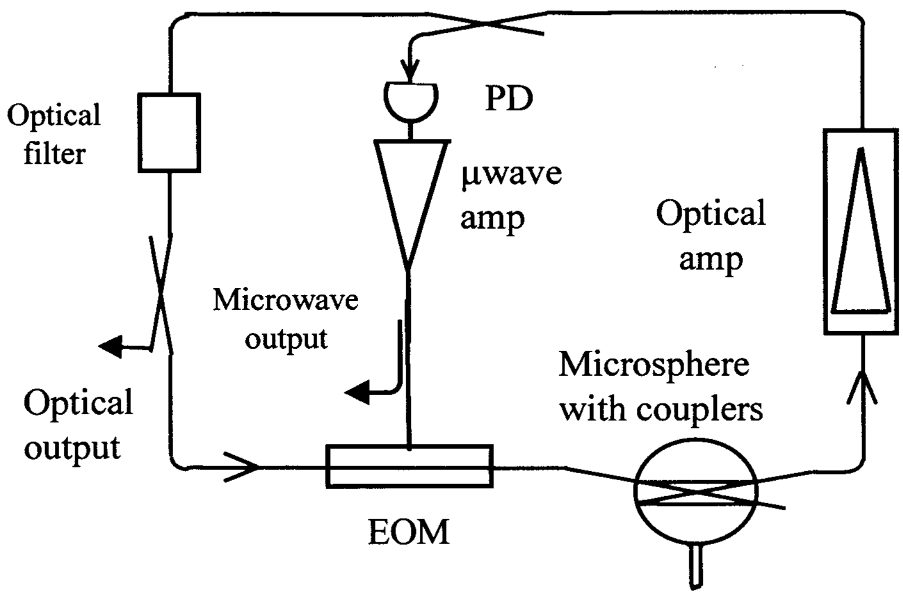
Spectrum of microwave oscillation in a complete ring-laser OEO with erbium-doped fiber-optic amplifier (Nortel FA-17) and tunable fiber-optic filter (DiCon TE-9-1565).

Microsphere diameter D~360mm; l=1,250; unloaded quality-factor $Q=1.2\times10^8$

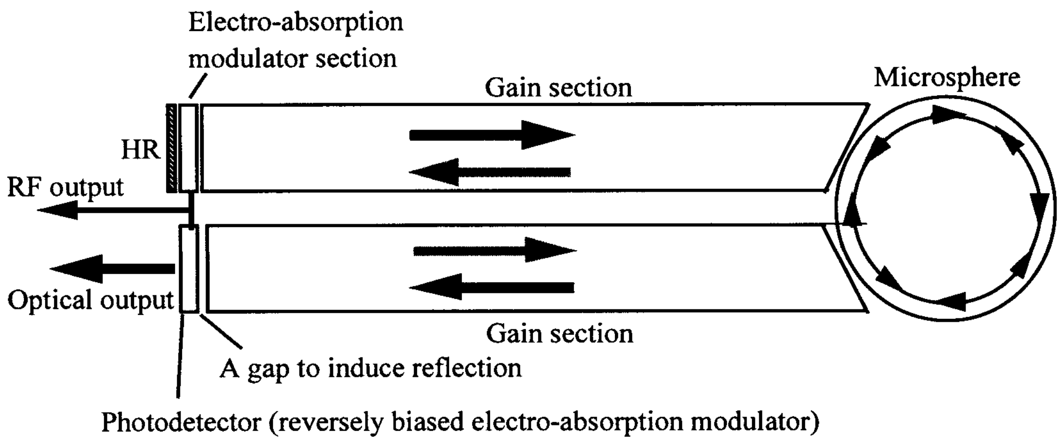




Device integration concept: OEO on chip

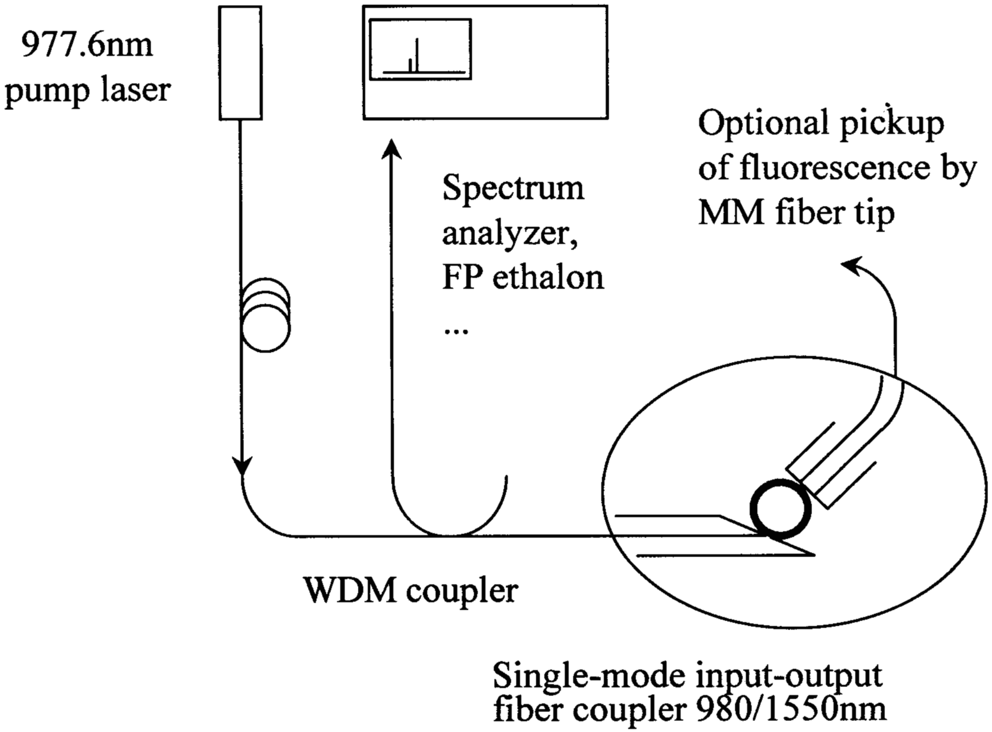


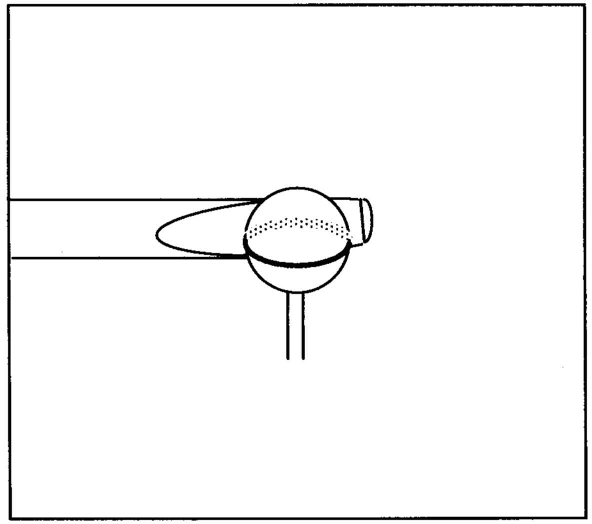
Discrete-element OEO

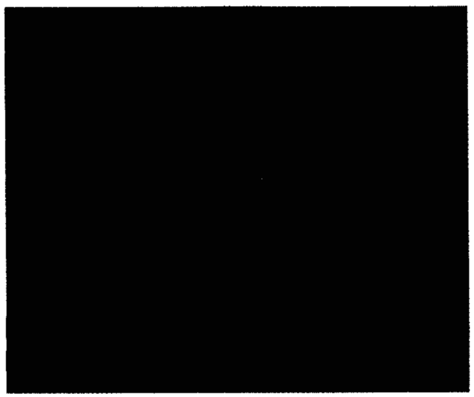


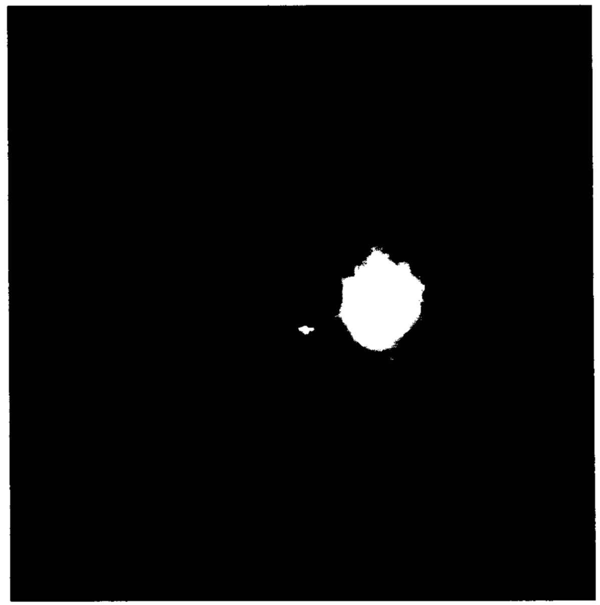
On-chip integration concept

A pigtailed erbium microlaser



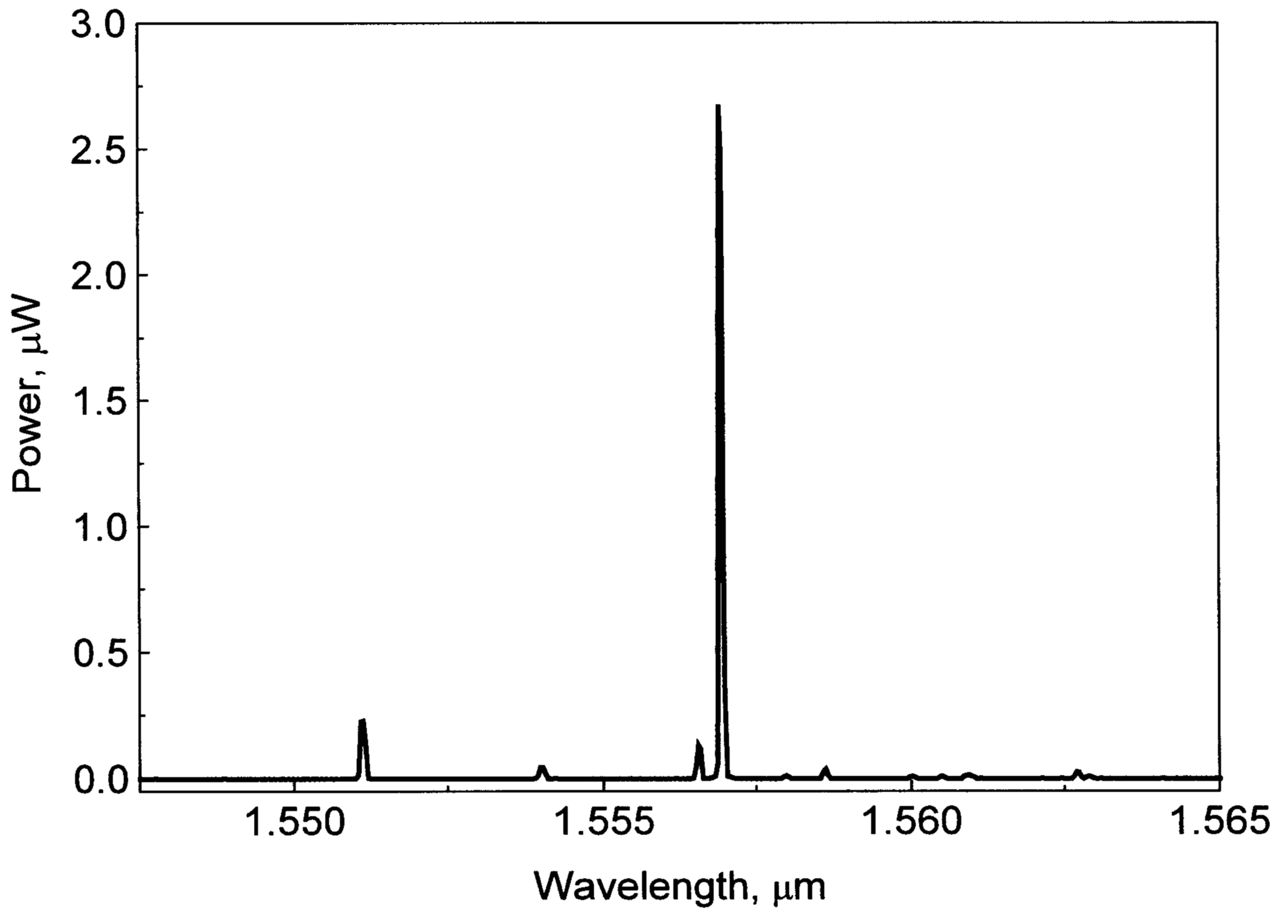






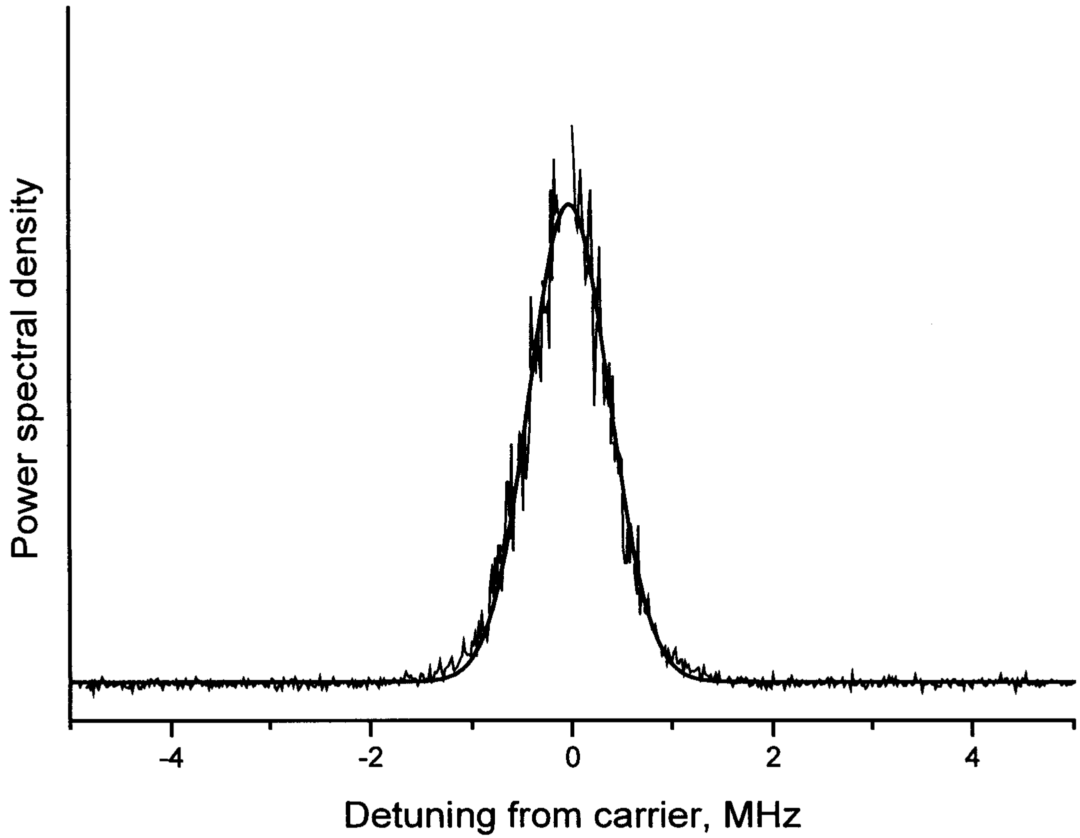
JPL

A fiber pigtailed erbium microsphere laser



Typical laser emission spectrum

A pigtailed erbium microlaser



Power spectrum of laser emission obtained by autocorrelation method.
Gaussian fit with 780kHz linewidth; predominant technical fluctuations.
5 second scan; 1kHz resolution BW

Novel geometry for WG microcavity

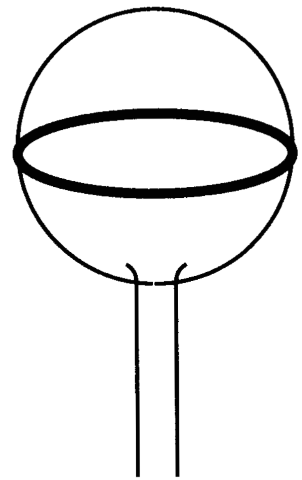
JPL

WHY SPHERES?

low material loss (transparent material)

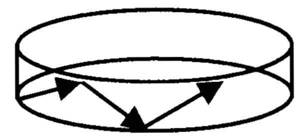
low bending loss (high-contrast boundary)

LOW SCATTERING LOSS (TIR always under grazing incidence) $\Theta \to \pi/2$; compare to disks/ rings:



$$\frac{I_R}{I_I} = e^{-(\frac{4\pi\sigma}{\lambda}\cos\Theta)^2}$$ (J.W.S.Rayleigh)

EVEN WITH MOLECULAR ROUGHNESS σ,
ONLY CURVATURE CONFINEMENT ALLOWS
Q LIMITED BY MATERIAL ATTENUATION !!

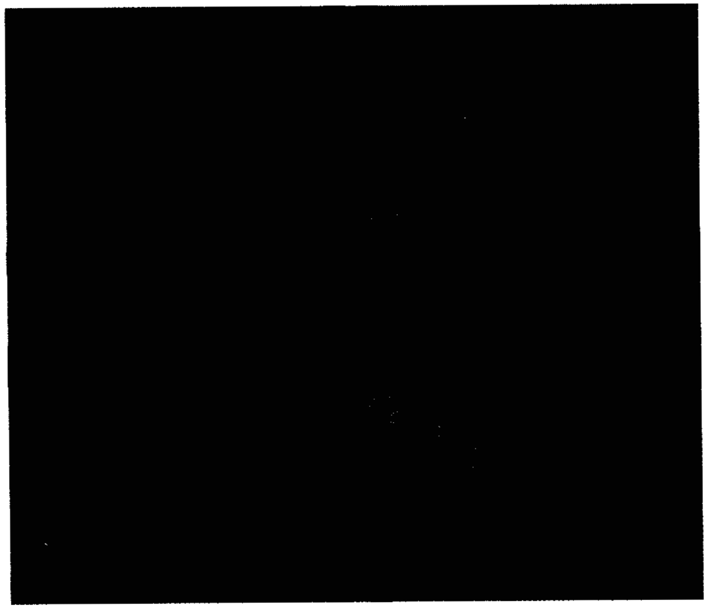


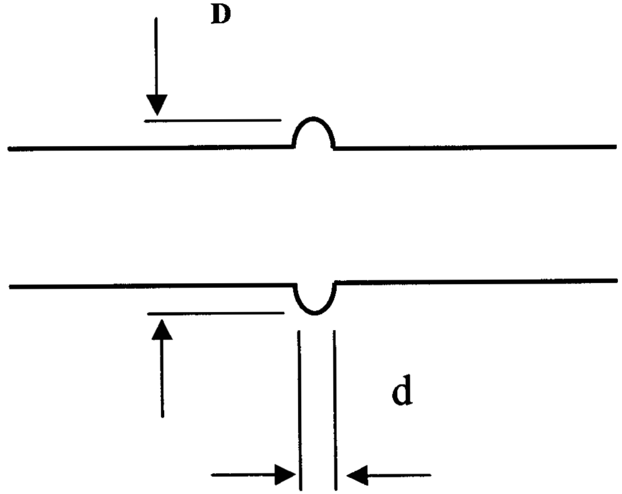
$10^8 \ldots 10^{10}$ in spheres vs. $10^3 \ldots 10^5$ in microrings

Drawback: "too many modes" compared to planar rings.

Novel geometry for WG microcavity

A solution.

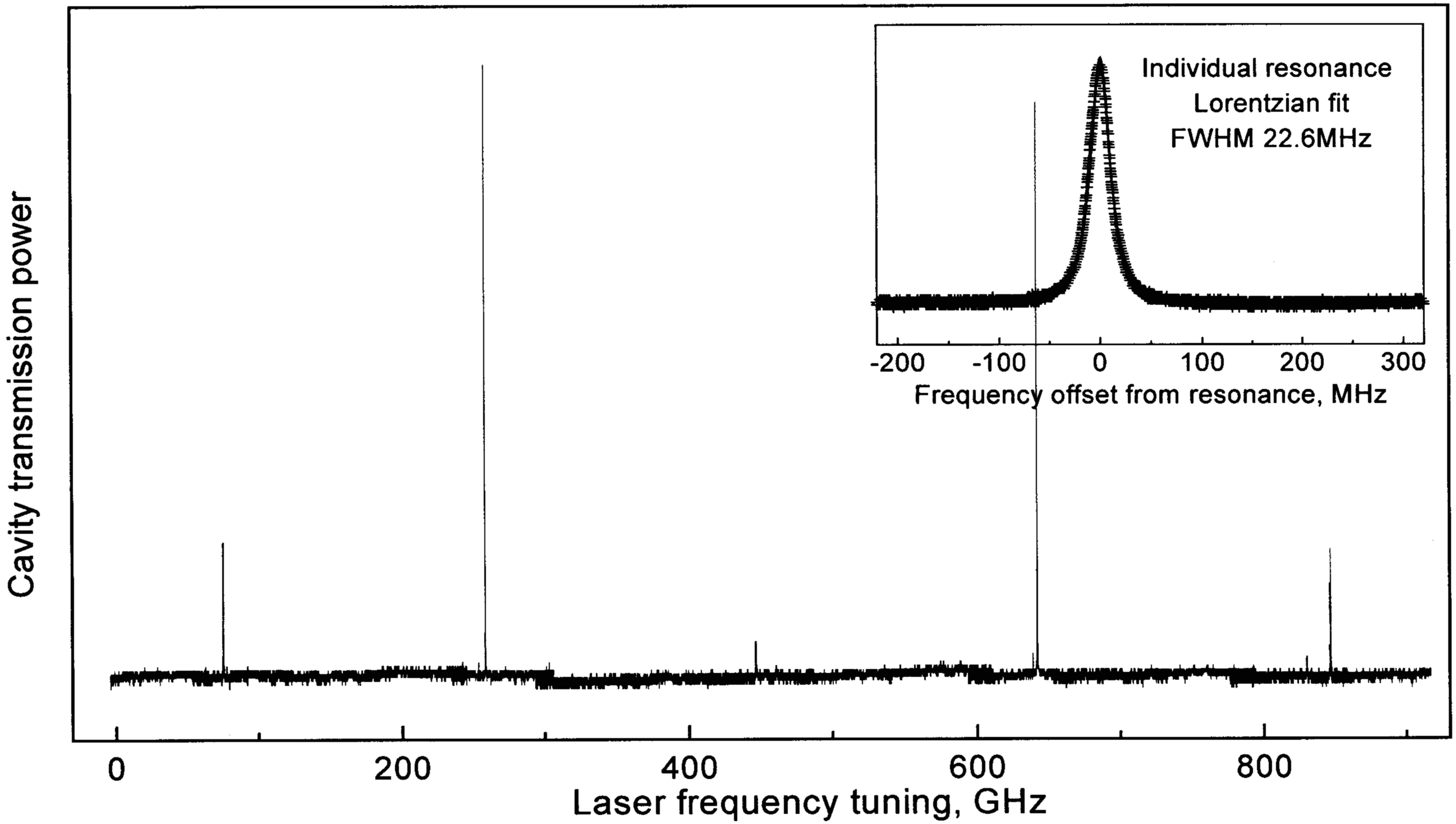




Microphotograph and the cross section of a novel geometry high-finesse dielectric microcavity with whispering gallery modes

Time and Frequency Science and Technology Group

Novel geometry for WG microcavity



Spectrum of whispering-gallery modes in spheroidal dielectric microcavity (D = 160μm; d = 35μm).
Free spectral range 383GHz (3.06nm) near central wavelength 1550nm.
Individual resonance bandwidth 23MHz (loaded $Q = 8.5\times10^{6}$). Finesse $F = 1.7\times10^{4}$